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RADIATION AND THERMALLY HARDENED SWITCHING MATERIALS

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In this year's work, we have been able to develop a method by which fast switching devices can be derived which have a high current carrying capability and are radiation hard. These devices are based on a junction between a conducting substrate and an oxide which can undergo a semiconductor to metallic transition. Example: NbO (metal)/NbO_2 (semiconductor to metallic transition at 807°C) or TiO (metal)/Ti_3O_5 (semiconductor to metallic transition at 135°C). We also have tried VO/VO_2 and it does work. However the off resistance is somewhat low and the device fragile because

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of the closeness to the actual transition temperature ($\sim 65^{o}C$). we have not had an opportunity to go in the details of the mechanism involved. It appears however that there are two distinct stages: one stage during which the junction behaves as Schottky diode, which is immediately followed by a stage of thermal runaway. More fundamental studies of this phenomena are certainly needed if we want to fully exploit its potential. In addition to systematizing production procedures of the chips, we have been able to use an industrially available standard package which proved very convenient.

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INTRODUCTION -

A systematic analysis of the results obtained in the previous work periods of the ongoing contract led to the conclusion that the switching phenomena originally observed in needle shaped crystal could not have been a bulk property of NbO_2 doped or not. Instead it occured to us that very high fields are needed and therefore we should try to switch thick films of NbO_2 on conducting substrates.

In accordance with this idea we manufactured a group of devices by heating in an oven at 800°C under a CO_2 atmosphere slices of NbO (about 5 mm in diameter and 1 mm thick), cleaved from single crystals grown by the Tri-Arc Chokralsky technique (NbO has metallic conduction at all temperatures). After 18 hours, the samples were allowed to cool down under CO_2, and we observed that a black coating had formed on the NbO chips which we assumed, until final verification, to be NbO_2. Consistently with this assumption the black films conferred a very high resistance to the samples. The chips were mounted in a pressure contact sample holder and found to switch in less than 20 nsec. (risetime of our Velonex pulse generator). Threshold switching voltage as observed was 400 V; current carrying capability was established to be larger than 30 A.

The switching was reliable, reproducible and no visible deterioration of the samples was observed after repeated pulsing.

On a transistor-scope, the I-V characteristic of all the samples showed a strong negative resistance region.

Samples of the first batch were provided to be tested at Fort Monmouth by Lt. Laplante, who, using faster pulses, determined the switching time to be smaller than 500 psec. with a protected voltage of 340 V. Current capability at the maximum protected voltage on a 50 Ω line was found to be 58 Amps.

VARIOUS PREPARATION TECHNIQUES -

Other preparation methods were tried to produce the devices:

1) growth of NbO_x (with $x > 1$) on NbO cleaved single Xtals in a furnace, under CO_2 gas at various temperatures and during various times.

2) growth of NbO_x by heating NbO cleaved single Xtals in closed quartz ampoules, in vacuum, in the presence of large amounts of NbO_2 powder, at various T and various times.

3) growth of NbO_x on Nb metal by the methods described above.

NATURE OF THE NbO_x LAYER -

In order to establish conclusively the nature of the NbO_x coating which was formed on the NbO chips we performed two tests. A first test was to run an X-ray diffraction pattern and the other was to examine a pure NbO crystal and a sample of the NbO_x films by ESCA.

X-ray difractometry of the prepared material shows exclusively the spectra of NbO_2 powder. A faint foreign line is observed which is probably due to NbO. This in itself is quite convincing . In addition our measurements indicate an NbO_2 thickness of ~ 1 µm.

ESCA measurements show a thin layer (~ 30 Å) of NbO_2 present in the "virgin" cleaved NbO starting material. This indicates, consistently with other works, that the first higher Nb oxide is NbO_2. Furthermore the ESCA spectra of our NbO_x films turned out to correspond exclusively to NbO_2. Consequently it would appear that the oxide formed is NbO_2 exclusively.

By changes in the same parameters, devices have been prepared with holding voltages from 3 volts up to 70 volts. We call holding voltage the voltage measured at the end of a 0.5 µsec. pulse.

By changes in the preparation procedures, it was possible to lower the threshold voltage (defined as the highest voltage that can be established across the device before switching takes place) from about 340 to 40 volts. In certain cases, threshold voltages as low as 3 volts were obtained.

PRELIMINARY STUDY OF THE SWITCHING MECHANISM -

Preliminary attempts to understand the switching mechanism involved in the discovered phenomena were started:

Figures 1 and 2 show the results obtained when trying to find a picture to describe in physical terms the conduction process.

Fig. 1 shows a plot of i vs. v for several devices. The data points were taken after the same elapsed time from the application of the pulse. Both i and v are the normalized values of I and V to the critical parameters I_c and V_c ($i = \frac{I}{I_c}$; $v = \frac{V}{V_c}$) where I_c and V_c are the values of current and voltage at the onset of the negative resistance region. According to Dr. D.C. Mattis of B.G.S.S., in the case where the switching proceeds entirely by thermal filament formation, the i vs. v curves for different samples taken at the same τ, if plotted in I_c vs. V_c, should fall on a single universal curve. As can be seen in Fig. 1, this is not the case which seems to indicate that the nature of the switching is not, at least, purely thermal.

Fig. 2 shows a plot of $\ln$ I vs. $V^{\frac{1}{2}}$. The values used in this graph are the same as those used before in Fig. 1. The graph clearly shows two successive straight lines dependence at the lower values of V and I. The points at which the straight lines character is interrupted may well have to do with the onset of a different mechanism for conduction. The linear dependent of $\ln$ vs. $V^{\frac{1}{2}}$ corresponds to the well known behaviour of a

Schottky barrier.

We then replotted the data shown in Figs. 1 and 2, using different assumptions.

Fig. 3 shows a plot of $\ln \frac{V}{I}$ vs. (V.I.) based on the same data used for the plot of $\ln I$ vs. $V^{\frac{1}{2}}$ in Fig. 2. In this figure it can be seen that the points on the curved portion of the $\ln I$ vs. $V^{\frac{1}{2}}$ plot fall now in a straight line in agreement with D. Mattis' theory of the dependence of the resistivity with applied power in the "off" region. This regime appears consistent with a thermal runaway that culminates in switching by a filamentary process.

Fig. 4 shows the same data as before plotted in $\ln I$ vs. $\ln V$ coordinates for the total "off" range. The two straight portions seen in Fig. 2 fit now, with some scatter, a single straight line corresponding to a law $I \propto V^{1.1}$ indicating a possible space charge limiting current process, followed by a thermal runaway as explained above. Clearly more work is needed to fully understand the switching mechanism.

Additional evidence for the electronic nature of the process before thermal runaway is presented in Fig. 5 where the I-V characteristic of a single surface NbO/NbO_2 device is shown. A strong asymmetry between the positive and negative voltage regions is observed. This is consistent with the expected behaviour of a junction type barrier. The asymmetry is not normally observed in symmetric double sided devices of the type $NbO_2/NbO/NbO_2$. When it does appear, the asymmetry is very small. Fig. 5 cannot be explained by simple thermal arguments.

A research program is necessary in order to clarify the nature of the process or processes involved and fully exploit them for device applications.

CONTACTS -

In view of the fact that the first part of the switching seems to proceed via an electronic process, the type of contacts, materials involved, their geometry and method of application could strongly modify the parameters of the switching devices. Increases of the capacitance due to the type and area of the contacts have the effect of increasing the switching time. Under the same circumstances, a decrease of the "off" resistance also worsens the situation by increasing the insertion losses. Experiments performed using graphite or NbO pressure contact pads, although increasing the capacitance of the devices from about 1 pF (for a gold point contact in one side and a rhodiated copper plate on the other) to about 3-5 pF, produced a decrease of the threshold voltage of about 30%. Accepting the likelihood of an initial electronic process, the graphite and NbO pressure contacts may be forming a barrier. The height and characteristics of the barrier will logically depend on the work functions of the NbO_2 and the electrode material. Further studies are being pursued to optimize these parameters.

B-TYPE DEVICES -

Attempts have been made at trying to develop a low voltage device by producing a different type of junction. Instead of NbO/NbO_2, we have attempted to make TiO/Ti_3O_5 devices. The method used was exactly the same as for the standards NbO/NbO_2 spike suppressors, i.e., we have annealed chips of TiO single crystals in sealed ampulas in the presence of an excess Ti_3O_5 powder. This process was successful and we did obtain a coating of Ti_3O_5 on the TiO chips. The devices did switch at relatively low voltage compared

to the NbO/NbO_2 devices. A typical device was submitted for evaluation to Lt. Laplante of AECOM. Preliminary results indicate that the switching voltage is of the order of 50 volts.

Simultaneously, we have conducted further investigations of our standard devices and found that it is quite possible, by changing the NbO_2 layer thickness or the electrode area, to lower significantly the switching voltage. Associated with these modifications are variations in the longevity of the devices under repeated pulsing. We are presently investigating these aspects of the problem.

PACKAGING -

Furthermore, our efforts have been directed towards packaging of the existing devices as well as systematization of production procedures. After discussion with Lt. Laplante of AECOM, we have tried one microwave diode package presently available on the market. The motivation is obvious since microwave diode packages are designed to minimize capacitance and induction. It is clear also that the problems encountered in building microwave diodes are quite similar to the problems we ourselves are encountering. In effect, our devices have turned out themselves to behave, at least in the first stage of switching, as Schottky barriers. While we were not too enthused with the fact that those packages are point contact systems, we also felt that this would be an improvement on the present pressure contact situation. The use of one of the packages turned out to be quite practical.

The typical off resistance of our devices in packages type 1N23 (X band) varies from 150 KΩ to ∞ depending on samples. The switching voltage is of the order of 100 to 130 volts and switching times as well

as current capabilities when checked by Lt. Laplante of US AECOM turn out to be the same as before, namely switching times faster than 500 p. sec. and current carrying of the order of 50 Amps. In addition, we found that the capacitance of the packaged diodes turned out to be smaller than 0.1 pFd.

CONCLUSION -

In conclusion, at the end of this year's work, we have developed a process by which fast switching devices can be produced which have a high current carrying capability and are radiation hard. These devices are based on a junction between a conducting substrate and an oxyde which can undergo a semiconductor to metallic transition. Example: NbO (metal)/ NbO_2 (semiconductor to metallic transition at 807°C) or TiO (metal)/Ti_3O_5 (semiconductor to metallic transition at 135°C). We also have tried VO/VO_2 and it does work. However the off resistance is somewhat low and the device fragile because of the closeness to the actual transition temperature ($\sim$ 65°C). We have not had an opportunity to go in the details of the mechanism involved. It appears however that there are two distinct stages: one stage during which the junction behaves as Schottky diode, which is immediately followed by a stage of thermal runaway. More fundamental studies of this phenomena are certainly needed if we want to fully exploit its potential. In addition to systematizing production procedures of the chips, we have been able to select successfully an industrially available standard package which improves considerably the performance of the devices, their mechanical stability and their longevity.

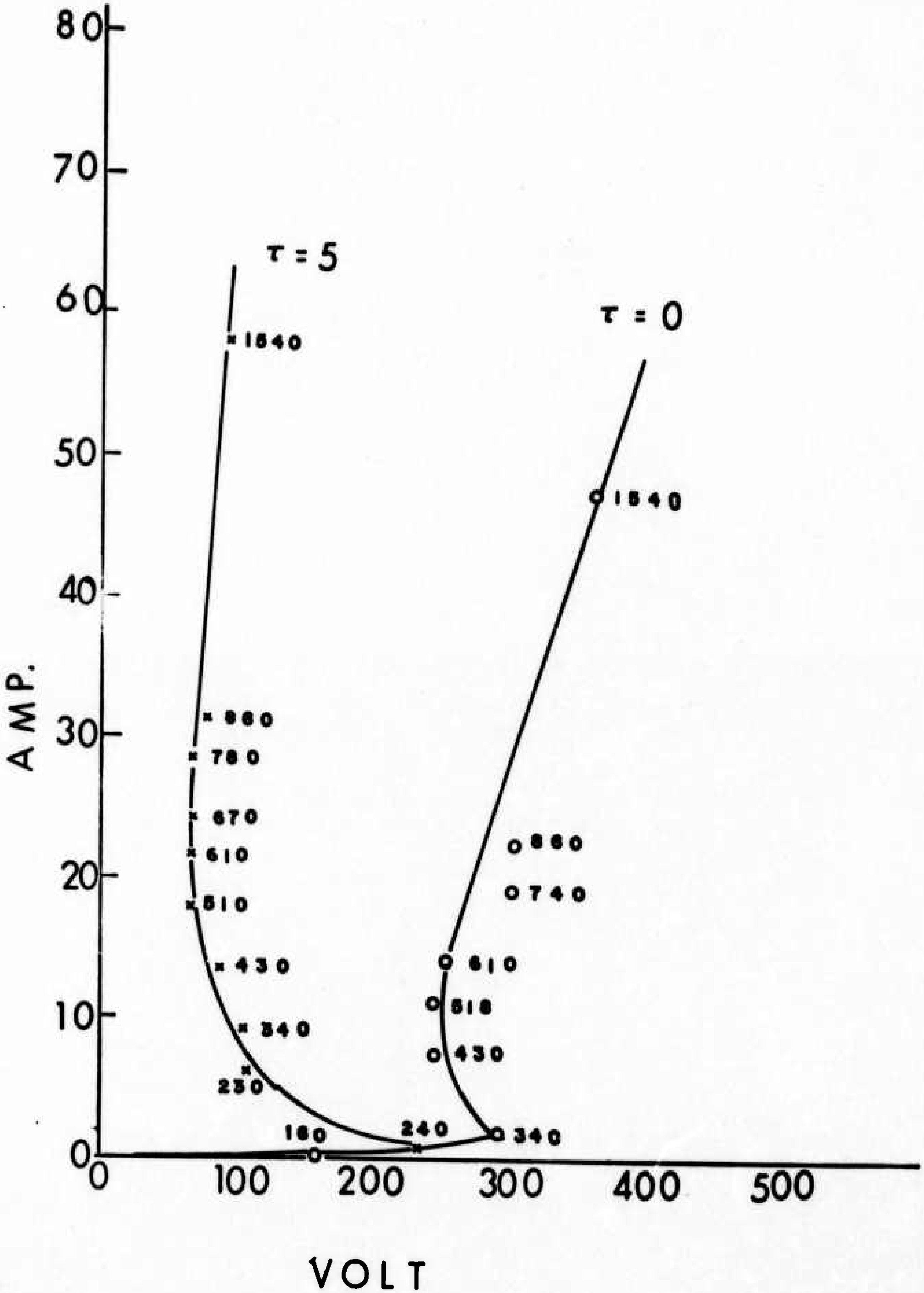

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Fig. 1

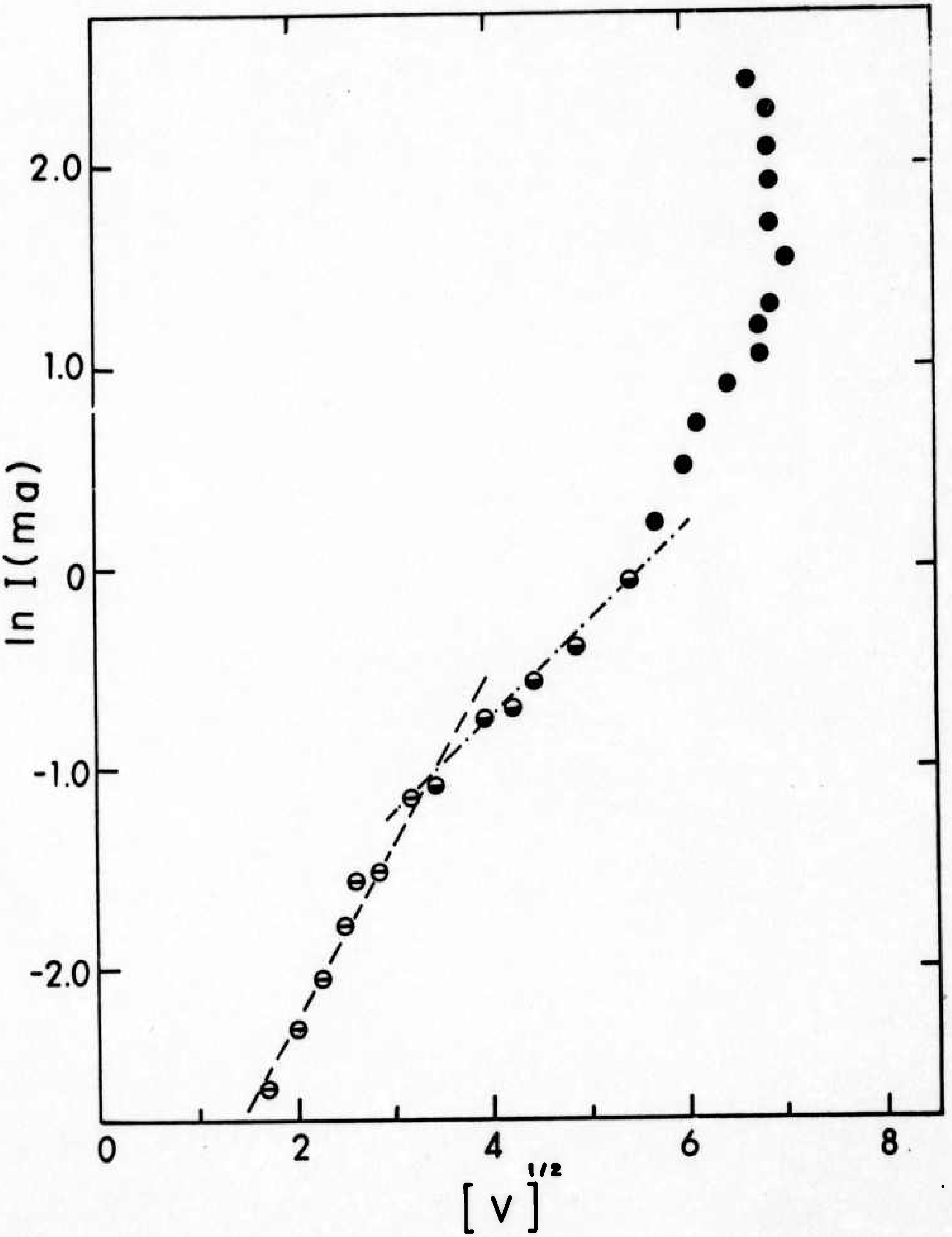

fig. 2

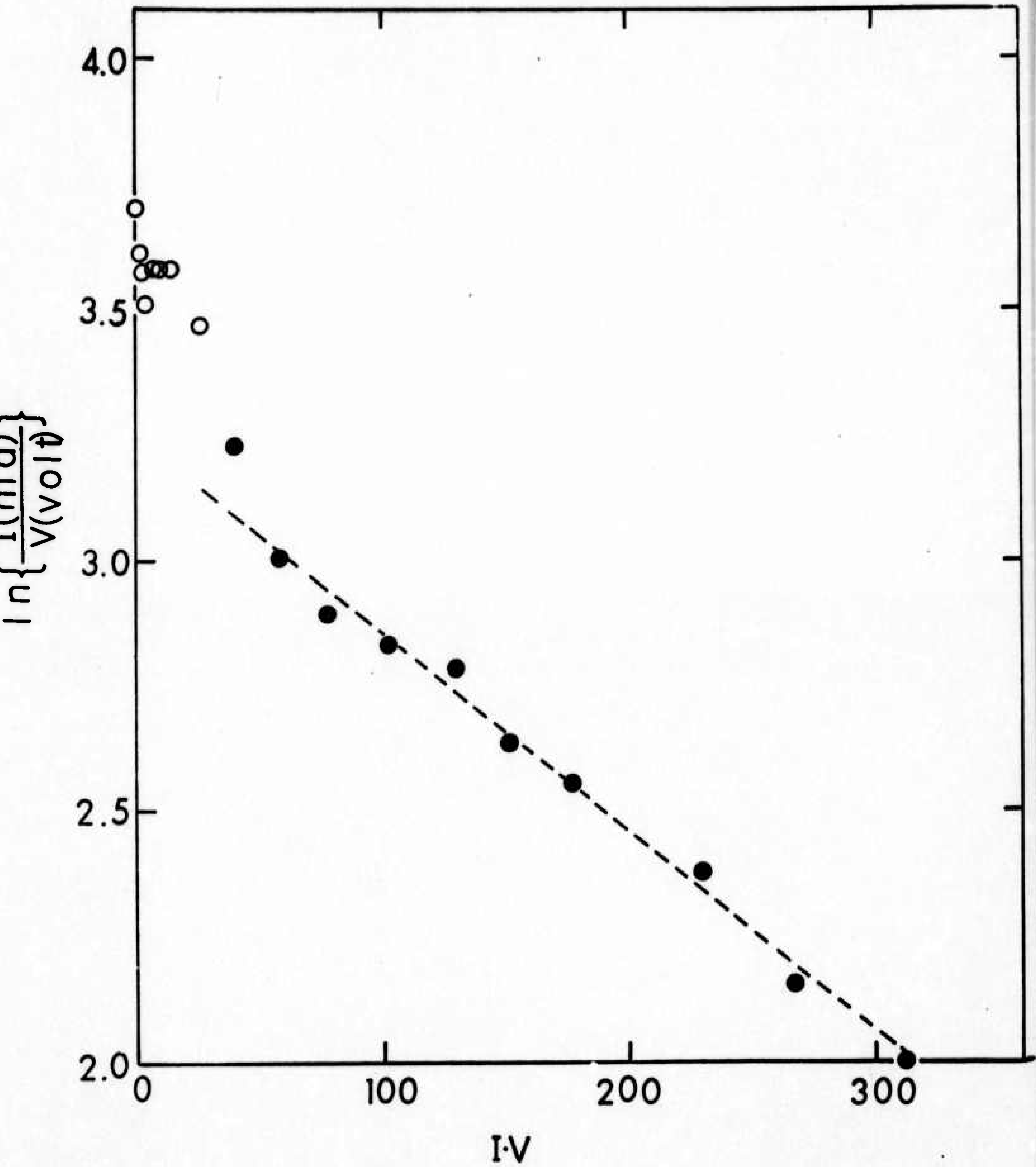

fig. 3

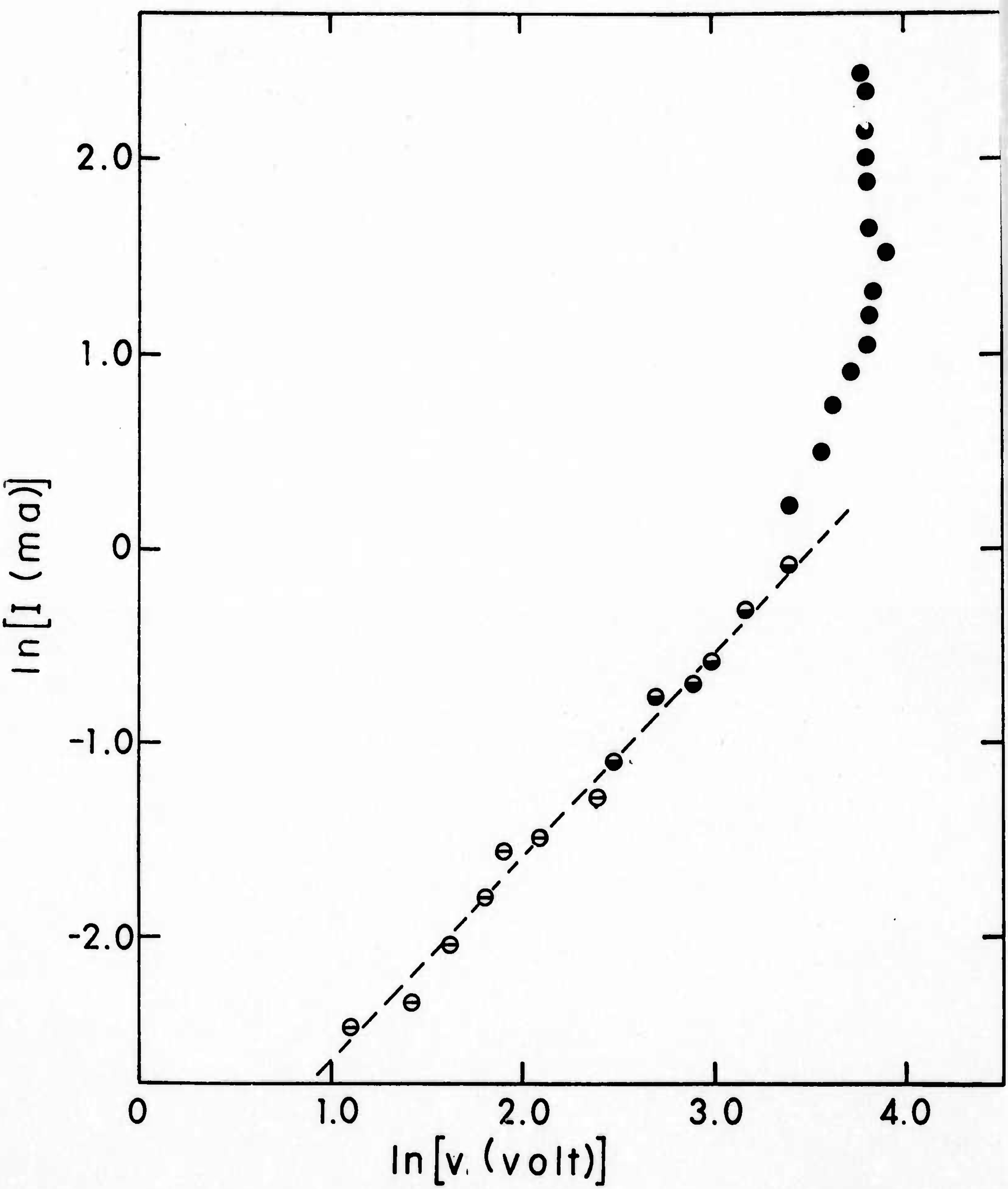

fig. 4

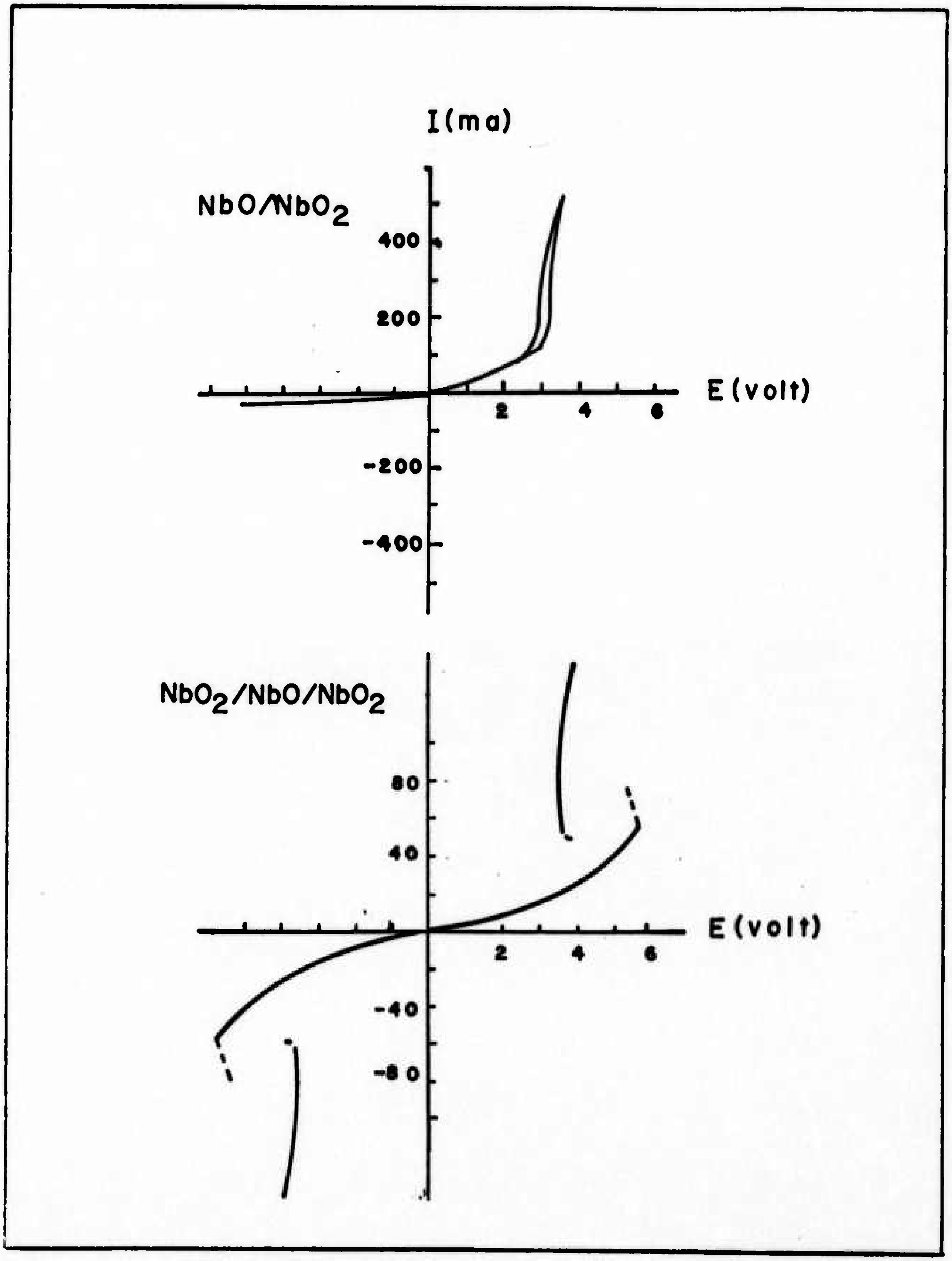
I(ma)
NbO/NbO2
400
200
-200
-400
E(volt)
2
4
6
NbO2/NbO/NbO2
80
40
-40
-80
E(volt)
2
4
6

fig. 5

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